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Multi-Well Experiment: A Field Laboratory for Tight Gas Sands

by D.A. Northrop and A.R. Sattler, *Sandia Natl. Laboratories*, and J.K. Westhusing, *U.S. DOE, BETC*
Members SPE-AIME

ABSTRACT

The Multi-Well Experiment (MWX) is a research-oriented field laboratory whose objective is develop the understanding and technology to allow economic production of the several years supply of natural gas estimated to be within the low permeability, lenticular gas sands of the Western United States. Features of MWX include: (1) close-spaced wells (~125 ft, ~38 m) for reservoir characterization, interference testing, well-to-well geophysical profiling, and placement of diagnostic instrumentation adjacent to the fracture treatment; (2) complete core taken through the formations of interest; (3) a comprehensive core analysis program; (4) an extensive logging program with conventional and experimental logs; (5) determination of in situ stresses in sands and bounding shales; (6) use of various seismic surveys and sedimentological analyses to determine lens morphology and extent; (7) use of seismic, electrical potential and tilt diagnostic techniques for hydraulic fracture characterization; and (8) a series of stimulation experiments addressing key questions. This paper presents the current MWX accomplishments in the above areas since drilling started at the site in September 1981 through December 1982.

INTRODUCTION AND BACKGROUND

New and improved technology is required to enhance gas production from the low permeability reservoirs of the United States. These reservoirs constitute a major target for new and supplemental supplies of natural gas. The National Petroleum Council's recent study estimates a maximum recoverable resource of over 600 TCF (17 Tm^3).[1] This gas is found in two broad categories of formations: continuous, blanket sands and discontinuous, lenticular sands. The latter are reservoirs characterized by lenses of low permeability sand of limited, variable lateral extent and thickness enclosed in a matrix of shales, mudstones, and siltstones. Most of the gas sands in four Rocky Mountain basins are lenticular. This several years supply of natural gas is the target for the Multi-Well Experiment.

References and Illustrations at end of paper.

The United States government's efforts to stimulate natural gas production from these reservoirs began in the mid-1960s. The early work evaluated the use of nuclear explosives for fracturing, but this technique was abandoned in 1973. Since that time, efforts have focused upon massive hydraulic fracturing and a total of nine government-industry, cost-shared field projects have been conducted. These were generally designed to be demonstrations of the then current industry fracturing technology as applied to these lenticular formations. The results were disappointing and did not yield either an improved technology or commercial production of this resource. The basic problem is that the past field tests provide insufficient data to define the critical factors affecting gas production from lenticular sands.

The intent of the Multi-Well Experiment is to uniquely determine factors affecting production and thereby provide a situation where uncertainties surrounding this resource can be resolved. This will be accomplished by a comprehensive geologic characterization of these gas sands and the evaluation of state-of-the-art and developing technology for their production.

Specific objectives for the Multi-Well Experiment are:

1) to determine the size, shape, orientation, and distribution of lenticular sands;
2) to determine in situ reservoir properties and quantify their variations within a lens and between lenses;
3) to improve reliability and accuracy of log interpretation in tight gas sands;
4) to determine the effects of earth stresses upon stimulation and gas production;
5) to conduct stimulation experiments to evaluate technology and answer key questions concerning production; and
6) to perform analyses and evaluations to assess the viability of gas production from lenticular tight gas reservoirs.

The key feature of the Multi-Well Experiment is two close-spaced wells. (A third well is planned in 1983.) Their 110-145 ft (33-44 m) separation is less than the nominal dimensions of the lenses in the area. Core, log, well-testing, and well-to-well seismic data will allow a far better definition of the geological setting than has been available previously. Extensive core was taken from each well through the 4000 ft (1200 m) thick Mesaverde formation. Comprehensive logging and core analysis programs were conducted. The close-spaced wells also allow well-to-well interference testing to obtain an accurate value of the in situ permeability, porosity, and anisotropy. One well is designated as the stress well and is being used to determine the vertical variation of in situ stress throughout the interval of interest. A series of stimulation experiments will be conducted and one well will be used as an observation well for improved fracture diagnostics and well testing.

The key to achieving the various Multi-Well Experiment goals is the synergism resulting from a broad spectrum of activities: geophysical surveys, sedimentological studies, core and log analyses, well testing, in situ stress determination, stimulation, fracture diagnostics, and reservoir analyses. The results from the various activities will define the reservoir and the hydraulic fracture. These, in turn, define the net pay stimulated: the intersection of a hydraulic fracture of known geometry with a reservoir of known morphology and properties. These definitions are further enhanced by the fact that most data will come from close-spaced wells. Thus, spatial variations in reservoir properties can be quantified.

The Multi-Well Experiment activities will provide many more pieces of the tight gas sands puzzle than previously available. Hopefully, enough pieces will be fitted together so that an overall solution, production from this unconventional gas resource, is possible on a reproducible and viable basis.

Further discussion of the rationale, plans, objectives and activities can be found in previous references.[2-4] The intent of this paper is to present an overview of accomplishments of the Multi-Well Experiment through December 1982. Coverage of each topic will be necessarily brief. Further information will be found in other MWX-related papers presented at this Symposium and at the special MWX poster session.

CURRENT ACCOMPLISHMENTS

(1) Two wells, 8350 ft (2545 m) deep and 135 ft (41 m) apart at the surface, have been drilled to establish a unique field laboratory for tight gas sands research. The two wells, MWX-1 and MWX-2, were completed between September 1981 and March 1982. In both wells, a 13-3/4 in. (0.35 m) surface hole was drilled with a low-solids, non-dispersed water-based mud system to approximately 4100 ft (1250 m), and 10-3/4 in (0.27 m) casing was set and cemented. The mud was then converted to a 90:10 oil-based emulsion mud system which was selected to improve hole stability and core recovery and quality. The wells were then drilled and selected intervals cored with 8-3/4 in (0.22 m) bits. Stratapax coring bits were used successfully for some intervals and rates of more than 6-10 ft/hr were obtained. Three pressure cores were also taken in MWX-2, the first time that the operation had been used in tight sandstones.

Significant gas shows were encountered throughout the section and mud weights from 10 to nearly 15 lbs/gal ($1.2\text{-}1.8 \times 10^3$ kg/m^3) were required from 5000-8000 ft (1525-2450 m). Both wells were completed with the setting and cementing of 7 in. (0.18 m) casing. An overview of coring and logging activities in the two wells in relation to the Mesaverde geologic section at the site is given in Figure 1.

(2) An unprecedented core analysis program is under way. Over 3700 ft (1100 m) of 4 in (0.10 m) diameter core, approximately 700 ft (210 m) of it oriented, was cut with a recovery of better than 99%: 2744 and 930 ft (836 and 283 m) in MWX-1 and MWX-2, respectively. This core was processed at a special field facility which included a core gamma assembly, newly developed tools for fracture orientation, special core measurements such as strain relaxation and collection of gas samples, photography, lithologic descriptions, core plugging and sampling, and handling and shipping. The core was then shipped to a core library at DOE's Grand Junction facility where it is controlled through a computerized inventory system.

Routine core analyses were performed on plugs taken at one foot intervals over all the sands encountered and into the rock abutting each sand, over 1400 plugs in all. Meaningful water saturation data were obtained from these plugs due to the oil-based mud: 70% at the top sands in the Mesaverde to 30%-35% at the bottom of the fluvial section and in the Cozzette.

Extensive special core analyses were also performed every 1-3 ft (0.3-1.0 m) across major sands and into the abutting caprock. These analyses included dry Klinkenberg and relative permeabilities under restored reservoir conditions, CEC measurements, capillary pressure, electrical measurements, mineralogy (including SEM and x-ray analysis), and rock mechanical property determinations. The initial results from these special analyses include the observations that:

(a) permeabilities at confining pressure of the coastal zone and Cozzette peak at 5-7 microdarcies, values which appear much less than the effective permeabilities suggested by gas shows and the first well tests;
(b) properties are more constant through, and from well to well in, the blanket sands than the lenticular sands;
(c) permeability variations across a lens correspond to the number of open pores seen in thin section; and
(d) the mudstones and siltstones abutting the fluvial sands have similar mechanical properties to the sands themselves, but that the expected property differences are found between the blanket formation and their bounding shales.

Over 1300 natural fractures have been found in the core. Those in sandstones are essentially vertical, contain calcite filling which may only partially fill the fracture, have widths of 1/32 in to 3/4 in (0.8-20 mm), and do not extend into the surrounding shales. In contrast, those in the confining mudstones or shales are characterized by low angle dips, slickensides indicating dip-slip motion, and absence of mineralization. The matrix permeabilities measured in core will not account for the observed gas production data to date. Therefore, other production mechanisms, such as fractures, are being studied.

Over 20 contractors and other interested organizations are involved in the core program. Other studies done or under way include strain relaxation, fracture characterizations, organic maturation, age dating of fracture filling, paleomagnetism orientation, natural gamma spectra and CEC measurements, and neutron capture measurements on plugs. This comprehensive program is yielding valuable information on the production from these tight formations.

(3) A comprehensive logging program was completed and improved interpretation techniques have been developed. Three different logging programs were run in MWX-1 and four different programs in MWX-2 as seen in Figure 1; these are listed in Appendix 1 of Reference 4. The high mud weight created problems with several of the logs and the limitation of the nonconductive oil mud precluded some desirable measurements and rendered others unusable. Operational problems inherent in a logging program of this magnitude came in the form of tool failure and tool unavailability.

Notwithstanding the above stated limitations, the MWX log data base is the best data presently available for researching tight gas sand logging problems and associated log interpretation solutions. Exceptional log quality resulted from a combination of outstanding hole stability, a conscientious effort on the part of the service companies and major oil companies that participated in logging, and rigorous log quality control field standards. Log quality is verified by extensive repeat logging and by overlap intervals for logging runs at different points in time.

Merged trace plots of multiple log runs are providing critical evidence of the role of permeability in controlling tight gas sand invasion profiles.[5] Invasion has much impact upon porosity and saturation interpretation.[6] The recognition of the degree of invasion shows promise as a quantitative permeability interpretation technique in tight gas sands.[7]

Raw log data are being utilized to understand the role of mud weight in affecting such basic measurements as photoelectric effect gamma and natural gamma spectral absorption. Response comparisons of thermal versus epithermal type neutron tools are possible as well as the potential for verifying and comparing the algorithms used for formation density versus lithodensity tools.

Log-core correlations of MWX data are facilitated by the superior quality multi-detector core-gamma log recorded in the field. This makes depth shifting a highly reliable procedure. Routine correlations with depth and porosities have been performed. More specialized correlations are under way, such as neutron cross section measurements on core to check neutron tool response in the formation. In addition, logging measurements and interpretation models are being compared to core data to solve specific problems, for example, variable matrix density.[8]

(4) Core and log data are providing a first look at sand continuity at close spacings (125 ft, 40 m) in a lenticular reservoir. A comparison of two gamma ray logs is shown in Figure 2. This short interval shows examples of continuity (5000-5050 and 5250-5300), thinning (5110-5160), discontinuity (5070-5080 and 5240) and variable properties (5000-5050). The sand percentage over the Mesaverde is between 40% and 45% except in the paludal region where it is 25%. The percentage of sands which are continuous between the two wells ranges between 100% for the blanket sands and 50% in the coastal interval. Statistically, these continuities over the well spacing provide a measure of sandstone body dimensions: 120-175 ft (35-55 m) and 1300-1700 ft (400-500 m) in the coastal and fluvial regions, respectively.

Additional insight into sand body morphology and sedimentology of the Mesaverde is that the formation outcrops along the Grand Hogback, approximately 11 miles (18 km) northeast of the MWX site.[9] The entire section is exposed at Rifle Gap, and studies there, in conjunction with MWX core and log data, have allowed subdivision of the Mesaverde into the different intervals shown in Figure 1 and described in Table I.

(5) A hydraulic fracture azimuth of $280 \pm 6^\circ$ is predicted based on the results of several pre-frac studies. These studies were of three different types:

(a) Geological observations at the earth's surface. Some 1630 surface fractures were mapped in the immediate vicinity of the MWX site and a fracture set characterized by conjugate shear was found. The bisector to this conjugate set is believed to be the maximum stress orientation and is $281 \pm 7^\circ$. This azimuth compares favorably with data obtained by the USGS in the northern Piceance Basin[10]: 280°-295° for lineaments and normal faults, 290° from minifracs to 2000 ft (600 m), and 280°-290° for surface fracture mapping.

(b) Analysis of geological and physical properties of oriented core. Twenty-seven vertical, filled fractures were found in oriented MWX core. As these showed no shear evidence, they may be analogous to induced hydraulic fractures and have strikes parallel to the maximum principal stress and show an average orientation of $279^\circ \pm 8^\circ$. Measurements of the anelastic strain relaxation indicated a maximum strain orientation of $285^\circ \pm 15^\circ$. Acoustic velocity anisotropies and differential strain analyses yield orientations of 270°-300° and $278^\circ \pm 12^\circ$, respectively.

(c) Computer modeling of expected stresses. A theoretical prediction of stress orientation resulting from variable topographic loads which dominate the MWX site indicates that the stress orientation could rotate northward from 273° at 4000 ft (1220 m) to 291° at 8000 ft (2440 m).

(6) Three seismic surveys (3-D surface, vertical profile, and well-to-well) have been conducted in an attempt to determine extent, trend and character of the sand bodies. The 3D surface survey was conducted to see if lenticular sand bodies could be resolved at this site and depths as they had been at a shallower site.[11] Analysis of data from the MWX site was complicated by terrain, electrical and seismic noise, and large irregular variations in fold density. The processing to date indicates that the maximum frequency available at the depths of interest is 40 Hz yielding a wavelength of 300 ft (100 m). This implies an available resolution of 150 ft (50 m) and about 40 ft (12 m) as a maximum. This should allow resolution of the blanket sands and other bodies with large lateral extent, but unlikely resolution of individual sand lenses.

Vertical seismic profiles were run in both wells for two shot locations (200 and 1900 ft (60 and 600 m) utilizing a triaxial locking geophone package. The near offset VSP resulted in good definition of reflectors in the paludal and blanket sands; there were differences in reflectors in the fluvial zone as seen in the VSPs from the two wells. The far offset VSP contained a larger shear wave signal than was expected, and more structure was observed in the shear wave records compared with the P wave records. The VSP data also yielded seismic parameters of the formation of important use to the other seismic surveys.

Well-to-well surveys were conducted in five zones (blanket, paludal, coastal, and two fluvial) by propagating broad-band, high-frequency seismic signals to receivers located at various positions in the receiving well. Velocity and attenuation data have been obtained and one- and two- dimensional analysis should be possible based on the high quality of the data.

(7) High resolution, accurate, minimum in situ stress measurements have been made. Five locations (to date) in and below the Cozzette formation have been tested by conducting small volume (<100 gal, 0.4 m^3) hydraulic fracture stress tests through perforations. For these small volumes, the instantaneous shut-in pressure is a good approximation of the minimum principal stress. Accurate, reproducible results were obtained by conducting a number of repeat injections in each zone of interest using a specially designed pump system, modified high-resolution electronic equipment, and a downhole shut-off tool.

The stress magnitudes were found to be dependent upon lithology. Marine shales below the Cozzette sands have large horizontal stresses which are essentially lithostatic with a frac gradient of 1.02 psi/ft (23.1 kPa/m). This indicates that these rocks do not behave elastically and processes such as creep and fracturing are the dominant mechanisms controlling the stress state. The sandstones and siltstones have much lower stresses with a frac gradient of 0.86 psi/ft (19.5 kPa/m). This is approximately the stress level expected from elastic considerations since the reservoir is overpressured at this depth. Distinct dual closures were observed in one test; such a response is consistent with the frac penetrating a thin sand surrounded by shales.

Additional stress measurements above the Cozzette and throughout the intervals of interest are a key feature of MWX.

(8) Well tests, including an interference test, have been conducted in the Cozzette formation. Two well tests were performed in the lower Cozzette sand. The initial test was a nine day drawdown followed by a two day buildup and revealed that the test was too short to adequately define the original reservoir gas permeability, although the data indicated a permeability in the range of 5-10 μd. Subsequently, an additional test was conducted that included a multi-rate nine day drawdown followed by a five day buildup. The flow rates obtained were significantly higher than in the first test, which indicated that the well was in the process of cleaning up. Standard Horner techniques, type-curve matching, and use of an advanced gas reservoir stimulator provided good history matching of the field data for this test. The derived reservoir gas permeability was found to be 400 μd. Thus, care is needed to insure accurate test interpretation.

An interference and pulse test was performed in the upper Cozzette sand using MWX-1 as the production well and MWX-2 (120 ft (36m) away at this depth) as the observation well. The test period was 15 days and very small pressure changes (~1 psi (7 kPa)) were observed in MWX-2. Flow rates in excess of 1 MMCFD (28 km^3/day) were achieved and indicated a substantial permeability. The time response of a few hours in MWX-2 following changes in MWX-1 substantiates that the relative gas permeability is high.

(9) A preliminary definition has been made for a series of stimulation experiments and the hydraulic fracture diagnostic techniques to be conducted at this field laboratory. The initial emphasis has been placed upon possible stimulation in the Cozzette and the coastal interval as prime examples of the contrasting blanket and lenticular morphologies. The paludal, a fluvial zone containing notable natural fractures, and other fluvial intervals, are also of ultimate interest. Specific objectives which the stimulation experiments can address include:

1) determining hydraulic fracture geometry in relation to lens morphology and properties in order to separate factors affecting gas production;
2) determining if lenses not in contact with the wellbore can be intersected and produced;
3) determining if a series of lenses in contact with the wellbore can be efficiently produced;
4) evaluating geologic/reservoir factors (e.g., water saturation, earth stress, rock type, etc.)

5) evaluating stimulation factors (e.g., fluid type, proppant type or concentration, fracturing rate, etc.);
6) verifying current hydraulic fracturing models and understanding; and
7) evaluating new stimulation techniques, as available.

A wide range of fracture diagnostic techniques will be used to obtain as much information as possible on fracture geometry and azimuth. The surface techniques are tiltmeter, electrical potential, and surface seismometers. Downhole techniques include borehole seismic, pressure, and the usual temperature and gamma ray surveys. The MWX site and depths provide a challenging environment.

CONCLUSION

The Multi-Well Experiment is a unique research-oriented field laboratory whose range of activities will answer key questions about the viability of, and production from, the lenticular, tight gas sand unconventional gas resource. This program is well under way and significant accomplishments have been made. An additional three years of stimulation and testing over the Mesaverde is planned at levels dictated by future funding decisions.

ACKNOWLEDGMENTS

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Table I.
Depositional Environments and Sandstone Morphologies

Zone	Depth	Description
Paralic	4000-4370 ft (1220-1330 m)	Appears to be a zone of returned marine influence with widespread, homogeneous sandstones and appears to be water saturated.
Fluvial	4370-6020 ft (1330-1835 m)	This major interval consists of irregularly-shaped, multi-story, composite sand bodies which were deposited by meandering stream systems. These sand bodies are expected to be on the order of 1000-2500 ft (300-750 m) in width and to contain abundant interval discontinuities.
Coastal	6020-6590 ft (1835-2010 m)	Characterized by deltaic distributary channel sand lenses. Most of the lenses are probably less than 200 ft (60 m) in width, average 23 ft (7 m) thick, and are interbedded with carbonaceous mudstones and siltstones.
Paludal	6590-7450 ft (2010-2270 m)	Contains thick, abundant coal deposits and several blanket sands similar to, but of more limited extent than, those in the lower zone. These are interspersed with lenticular, distributary channel sandstones formed in a lower delta plain environment. The sand percentage (26%) is markedly lower than in other zones.
Marine	7450-8350 ft (2270-2545 m)	Contains the Corcoran, Cozzette and Rollins sandstones and was formed on either side of an oscillating coastline and is composed of widespread (~ 50 mi, ~80 km) shoreline-to-marine blanket sands, marine shales, and paralic coals.

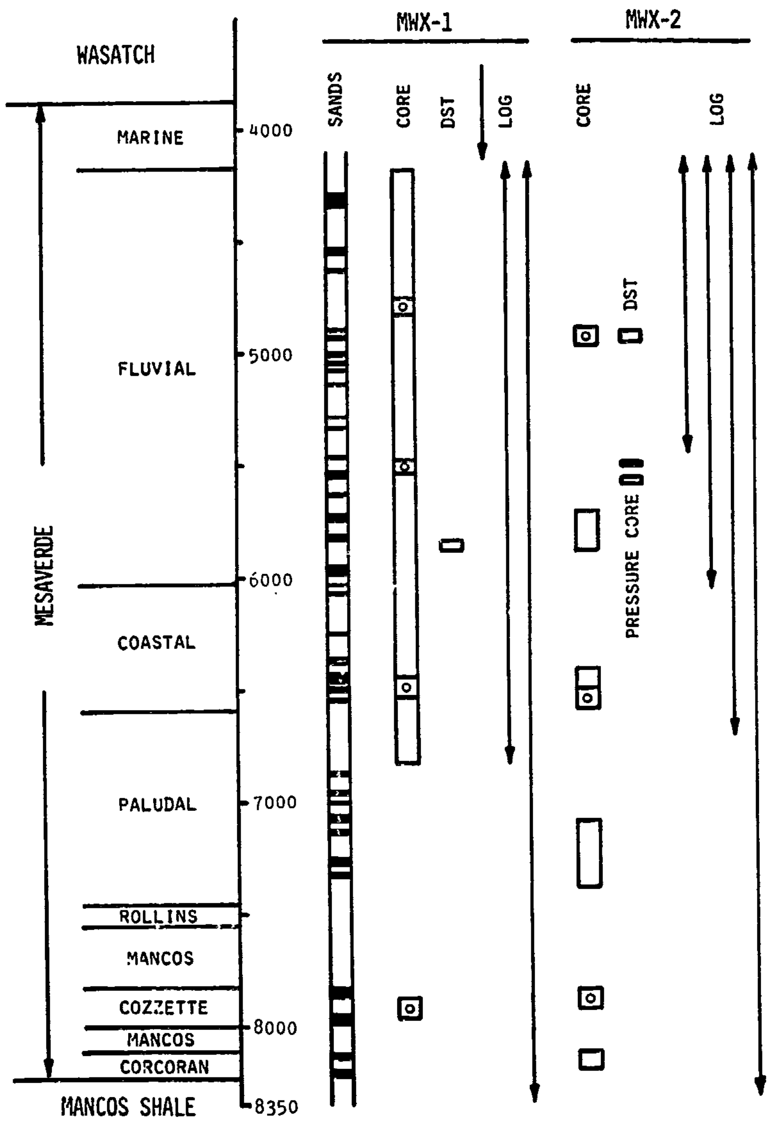

Fig. 1—Geology of the Mesaverde and summary of MWX-1 and MWX-2 activities.

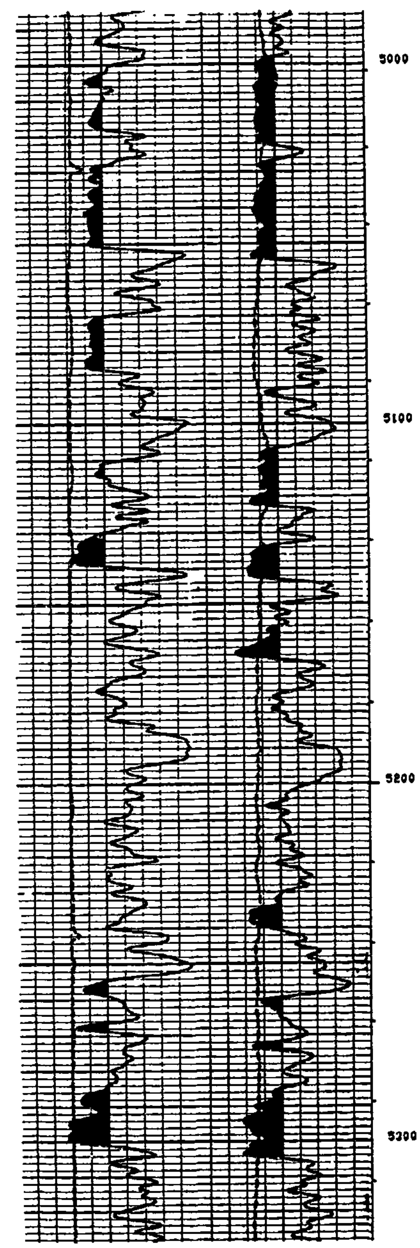

Fig. 2—Comparison of sands in MWX-1 (left) and MWX-2 (right). (Gamma ray log; different calibrations.)

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